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In this final report we summarize our research accomplishments during the support period of this grant. The scope of this research program is to carry out fundamental research in several areas: (a) the use of multiresolution methods in statistically optimal image analysis; (b) the blending of sensor physics and statistical models for computationally efficient, near-optimal inversion and image formation with applications in radar imaging; (c) the development of statistically robust and computationally efficient nonlinear image processing methods with applications in segmentation, edge detection, and feature extraction for object recognition; (d) the development of multiresolution and wavelet-based methods for robust feature extraction, with applications in object recognition; (e) the development of fast numerical methods for a number of difficult problems in statistical image processing; and (f) the extension of our multiresolution modeling framework to include very different granularities of information. from image pixels to discrete variables representing context, with applications to the emerging areas of global awareness and integrated spatial databases.

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Final Technical Report for
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MULTIRESOLUTION METHODS IN SYSTEMS, SIGNALS, AND IMAGES

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I. Summary: Objectives and Status of Effort

In this report we summarize our accomplishments under the research program supported by Grant F49620-98-1-0349. The basic scope of this research program is to carry out fundamental research in several interrelated areas: (a) the use of multiresolution methods in statistically optimal image analysis, with applications in multisensor fusion, image segmentation, anomaly detection, and optimal processing in the presence of speckle; (b) the blending of sensor physics and statistical models for computationally efficient, near-optimal inversion and image formation with applications in radar imaging and other areas of interest to the Air Force; (c) the development of statistically robust and computationally efficient nonlinear image processing methods with applications in segmentation, edge detection, and feature extraction for object recognition; (d) the development of multiresolution and wavelet-based methods for robust feature extraction, with applications in object recognition; (e) the development of fast numerical methods for a number of difficult problems in statistical image processing using a blend of advanced numerical methods and our work on multiresolution algorithms; and (f) the extension of our multiresolution modeling framework to include very different granularities of information, from image pixels to discrete variables representing context, with applications to the emerging areas of global awareness and integrated spatial databases. Key features of this proposal are that (i) it blends together methods from several fields--statistics and probabilistic modeling, signal and image processing, mathematical physics, scientific computing, Bayesian networks, and nonlinear differential equations--to produce new approaches to emerging and challenging problems in signal and image processing; (ii) it both builds on the research results we have obtained under our current grant and also explores new directions in which our approaches appear to have significant merit; and (iii) each aspect of the proposed program contains both fundamental research in mathematical sciences *and* important applications of direct relevance to Air Force missions.

The principal investigator for this effort is Professor Alan S. Willsky. Professor Willsky has been assisted in this effort by Dr. John Fisher, a research scientist in MIT's Laboratory for Information and Decision Systems, and by several graduate research assistants as well as additional thesis students not requiring stipend or tuition support from this grant. In the next section we describe our research accomplishments; in Section III we indicate the individuals involved in this effort; in Section IV we list the publications supported by this effort; and in Section V we discuss interactions and transitions.

II. Accomplishments/New Findings

In this section we briefly describe the research accomplishments we have achieved with support provided by this grant. We limit ourselves here to a succinct summary and refer to the publications listed at the end of this report (as well as the previous progress reports) for detailed developments.

2.1 Multiresolution, Hierarchical, and Relational Modeling

The research described in this section is developed in great detail in a number of papers and reports [1,3,6,17,19,22,27,33,34,41,44,60-63]. The overall objective of this portion of our research is the development of methods for constructing stochastic models for phenomena that vary over space, time, and hierarchy and that possess structure which can be exploited to construct efficient and scaleable algorithms for statistical inference (the subject of subsequent sections of this report).

a) As we described in our earliest work on multiresolution models on trees, each node on the tree in a multiresolution model separates the tree into several disjoint subtrees (corresponding to the disconnected components of the tree if that particular node were removed). The role of the state at that node is to act as a statistical interface between these subtrees. That is, conditioned on the state at that node, the sets of variables in these disjoint subtrees are mutually uncorrelated. In our early work in this area we combined this characterization of state with a generalization of the notion of canonical correlations to develop a first approach to constructing multiscale models that yield statistics for the finest-scale process (i.e., the variables at the finest-scale leaf nodes of the tree) that approximately match those of a given stochastic process or random field. This approach to building multiresolution models, while providing excellent models for stochastic phenomena that we had not been able to model previously, had significant limitations and drawbacks, many of which have been exposed in our recent work [34]. First of all, the use of canonical correlations as the criterion for determining state variables at each node is extremely complex computationally. Secondly, the use of the criterion of maximal decorrelation is not necessarily the right one to use. In particular, as argued in [34], the reason for constructing multiresolution models is that they then provide the basis for very efficient statistical inference computations, e.g., for the calculation of optimal estimates of the phenomenon being modeled given noisy and possibly incomplete observations. This suggests that perhaps a better criterion for designing a state variable at a node on a tree is to choose states that do the best job of estimating variables at the leaf nodes of one of the subtrees given measurements of the leaf nodes on another of the subtrees. Not only does this approach lead to the definition of state variables designed in a manner more consistent with the ultimate use to which the model will be put, but it also leads to a dramatic reduction in computational complexity.

Moreover, in [34] we also provide a deeper interpretation of what the state variables are. In particular, in its most general and unconstrained form, the states in a multiresolution model at all but the leaf nodes are simply hidden variables, designed simply to fulfill their role in statistically decorrelating the subtrees extending away from each node. However, in many cases we want these variables to have real physical significance, namely that they truly do represent coarser versions of the finest scale process. Adopting terminology from state space realization theory for time series, a multiresolution model in which each state consists of a set of nonlocal, coarser functionals of the finest-scale process--is called an *internal* model. In [34] we provide a complete theoretical characterization of the properties of states of internal models which, in particular, shows that these states have a scale-recursive structure from *fine-to-coarse*. That is, much as in

wavelet analysis, each state in an internal multiscale model consists of nonlocal functionals of its immediate descendent. In [34] we develop an algorithm that not only produces internal stochastic models but that exploits the fine-to-coarse characterization of internal states to achieves even greater computational efficiency. The bottom line is that, while our previous algorithm had $O(N^4)$ complexity, where N is the number of leaf nodes in the tree (e.g., the number of pixels in the image of interest), our new algorithm has complexity that has $O(N^2)$ complexity.

b) The second component of this portion of our research involves the rapprochement of our multiresolution methods with the machinery of wavelet analysis [22]. This is nontrivial intellectually, as it provides a different way in which to view wavelet functionals. In particular, while wavelets are usually thought of as a tool for *analyzing* signals and images, we have now shown how we can incorporate some of the machinery of wavelets into our multiresolution framework which focuses on *modeling* signals and images. In particular, by making this embedding, our statistical methodology naturally leads to a very different method for coarse-to-fine signal modeling--namely statistically optimal coarse-to-fine prediction--than that suggested by standard wavelet synthesis. Combining this with the theoretical concept of an internal multiresolution model, we have shown that we can obtain remarkably accurate models of fractal processes with very low-order wavelets--indeed far lower order than is achieved by standard wavelet methods. Moreover, since the focus of our methodology is first on building models rather than on analyzing data, we can directly use these same models to solve problems which are not easily or naturally considered within the usual wavelet framework--e.g., statistical reconstruction based on sparse and irregularly sampled data, optimal fusion of multiresolution measurements, etc.

c) In the third portion of our research in this area (described in detail in [41), we have developed a major new result that addresses a significant issue not considered in our previous work on building multiscale models. In particular, all of our other work on multiscale modeling assumes that we have available the entire covariance of the fine scale process to be modeled. In many applications this is not reasonable for two reasons: (i) for large fields we may not know the entire covariance, i.e., the covariance between every fine-scale pair of points in the field being modeled; and (ii) even if we did know this entire covariance, explicitly storing or using it in a realization procedure quickly becomes prohibitive for large problems. Thus we have looked at the problem of building a multiscale model (which implicitly specifies the entire covariance) directly from knowledge of only a part of the fine-scale covariance matrix. This turns out to be a novel variant of the intensely studied problem of covariance extension.

In our work we have looked at what starts out as a standard problem: we are given a diagonal band of the covariance matrix. What is well-known is that the max-entropy extension of this covariance is a Markov process of order equal to the width of the specified covariance band, and the celebrated Levinson algorithm allows one to specify not only this extension implicitly through a time-dynamic model but also to characterize all possible extensions in terms of so-called partial correlation coefficients. This algorithm allows one to compute missing covariance elements band-by-band, extending outward from the specified band. What we have developed is a significantly nontrivial extension of this idea that involves filling covariance elements in very different orders. The motivation for this extension is our earlier work that showed that Markov processes can be modeled exactly on a multiscale tree. Constructing the parameters of this multiscale model requires knowledge of certain elements of the overall covariance that do not at all fall in a banded structure but rather require filling in a fractal pattern of elements in the covariance matrix. In seeing if one could indeed do this efficiently, we developed new graph-theoretic results that characterize sequential orders in which covariance elements can be computed efficiently and to which Levinson's algorithm can be extended. We then also show that the elements

required to be filled to construct our multiscale model indeed satisfy the conditions of our graph-theoretic result, allowing us to build multiscale models efficiently. We believe that this result is quite significant, not only because of its contribution to a very challenging and widely studied theoretical problem but also because the graph-theoretic machinery we have developed opens up many interesting and important research problems.

d) A broad area for the extension of our multiresolution methodologies is to non-Gaussian and nonlinear models. In [44, 61-63] we describe some of our recent work motivated by the statistical behavior of wavelet coefficients of real imagery. In particular, while wavelets are known to do a good job of decorrelating images, the resulting wavelet coefficients are generally neither Gaussian nor independent. In particular, the empirical distributions of these coefficients generally show heavy-tailed behavior with sharp peaks at zero. Moreover, there are characteristic dependencies among "neighboring" wavelet coefficients (neighbors in location, scale, or orientation for steerable 2-D wavelet pyramids) in which if one coefficient is large there is a higher probability that its neighbors are as well. It is precisely this type of behavior that is exploited in wavelet-based compression algorithms such as embedded zero-trees. Motivated by these empirical observations, we have begun to develop a framework for capturing what we refer to as "wavelet cascades" which capture both a variety of heavy-tailed distributions including α-stable processes as well as the self-reinforcing cascade of large wavelet coefficients.

The model class described in [62] captures these characteristics with a construct that has a great deal of structure. In particular, our models involve the use of general Gaussian mixtures as a method for generating a variety of heavy-tailed distributions. More precisely, our model involves the multiplicative mixing of a linear-Gaussian multiresolution model with a memoryless nonlinear function of a second multiscale Gaussian process (known as the "multiplier" process). By adjusting the scale-to-scale correlation of these processes and the shape of the memoryless nonlinearity we can model a surprisingly rich set of heavy-tailed behavior that exhibit the types of cascade phenomena found in real imagery. Thanks to the structure of these models, we believe that they represent fertile ground for detailed analysis and algorithm development. Indeed in [62] we present some preliminary resluts showing how this structure can be exploited in developing efficient estimation and fusion algorithms.

e) In other recent work [37] we have initiated an effort aimed at the development of nonparametric statistical methods for constructing multiresolution models for applications ranging from object recognition to data mining. In particular the construction of multiscale models involves two distinct steps, the identification of the state variables to be used at each node of the tree and then the identification of the coarse-to-fine multiscale statistical model. In the context of linear-Gaussian models, the second of these is comparatively straightforward and is roughly comparable to the one-step prediction problem for time series (although on trees, each parent node has several children requiring prediction steps). In the case of nonlinear multiresolution models, both of these steps are highly nontrivial, and in our initial work we have focused on the second one. That is, in our work to date we have fixed a priori the variables that comprise the states at each node and then seek to build nonparametric coarse-to-fine statistical models relating these variables. The specific context for our initial work in this area is SAR-based ATR, a subject described in subsequent sections of this report. What is of significance for this section of our discussion are the novel aspects of the problem of building nonparametric models for the coarse-to-fine predictive model. As in the other aspects of our work, the fact that we have a tree introduces new issues not encountered for time series. In particular, in time series analysis, stationarity or local stationarity is invoked in order to obtain some stability to the estimates of the time series model: e.g., we assume a stationary distribution for successive data points and thus can use each successive pair of data points as a sample from the

distribution, providing a significant number of samples. What types of stationarity make sense on a tree? Across nodes at the same scale? Across scale? Furthermore, we now have several parent-child data pairs with the same parent but different children. Obviously these are not independent samples since they share the same parent, but each such pair does contain additional information. How do we account for this? In our initial work [37] we have both posed these questions and taken very preliminary looks at them, yielding models for SAR data that we have then used for object discrimination with sufficient success to make clear that further pursuit of these issues is warranted.

f) The motivation for this portion of our research [7,10,21,42-43] is the problem of fusion of data for spatially-distributed phenomena or imagery that also evolves in time. The challenge in such problems is readily seen when one looks at their time-recursive structure. In particular, from this perspective, the problem can be seen as one of propagating estimates of entire spatial random fields at successive instants in time together with the propagation of models of the uncertainty in these estimates (as these models are then needed to specify the statistically correct way in which to assimilate data in the future). Brute force application of standard recursive estimation concepts (e.g., like the Kalman filter) lead to approaches that do not scale at all well with domain size and in fact become prohibitive even for comparatively small spatial domains. The perspective we have adopted in our initial work is to develop algorithms that directly propagate multiresolution statistical models for estimation errors as time evolves and as we incorporate new data. The idea here is that such models, which specify the error statistics implicitly (rather than explicitly as in the standard Kalman filter), admit fast algorithms for incorporating new data as we indicated in the preceding section. The key, then, is finding efficient methods for propagating such models over time.

Our initial investigation in this area involved the study of 1-D space-time problems, for which we have demonstrated that nearly optimal performance can be achieved with computational load per time point that grows as $N\log N$, where N is the number of points in the spatial domain. This compares to the N^3 complexity per time point for standard Kalman filtering. The key innovation here involves developing a method for propagating a multiscale model for the spatial uncertainty in a random field across time, where the temporal dynamics has the effect of "mixing" scales in the field. Because of this mixing, the statistics relating variables at different scales changes, and computing these new statistics and then calculating the scale-to-scale dynamics of the new multiscale model for this temporally-mixed field is a computationally prohibitive task if done explicitly without exploiting any structure. We have been able to overcome this computational obstacle precisely through such exploitation. In particular, in our work we have focused on models in which the temporal models involve two fundamental mechanisms: transport, in which spatial variables are in essence carried along by a flow field, and diffusion, in which there is spatially local mixing that takes place. While our most complete demonstration of the effectiveness of this method is for problems with a one-dimensional spatial domain, our method suggests ways in which to extend this concept to higher spatial dimensions.

2.2 Sensor Fusion Algorithms over Space, Time, and Hierarchy

The research described in this section deals with efficient algorithms for large-scale optimal estimation and is reported in detail in [2,5,7,9-10,18,20-21,26-27, 29, 35-36,42-45,60,62-63,68]. The general objective for this part of our research is to investigate stochastic models with structure that can be exploited in order to develop optimal or near-optimal algorithms that are scaleable to the large-scale problems encountered in image analysis, sensor fusion, and higher-level fusion. In our work we have demonstrated the power of multiscale linear/Gaussian models on trees in terms of the efficient algorithms that such models exist. Our most recent aimed at significant extensions of the class of models

for which we can obtain algorithms that are as powerful or nearly as powerful as those for linear-Gaussian models on trees.

g) The predominant algorithmic concept that is under investigation by researchers in the field of graphical models is Pearl's algorithm, which involves utilization only of the local structure of a graph, ignoring global structure such as loops. While some convergence results (both positive for estimates and negative for error covariances) exist, there is a fundamental limitation to this approach, namely its exploitation only of local structure. Thus, in particular, one might expect this algorithm to have the same slow convergence properties as Gauss-Seidel algorithms for large linear systems corresponding to standard MRF models on 2-D lattices or to elliptic PDE's. Our very recent work [44,60] is aimed at exploiting global structure explicitly. Indeed, this is exactly the point of our tree algorithms. That is, it is precisely the global structure of trees (i.e., the absence of loops) that allows us to propagate estimates very efficiently throughout the entire graph. In very recent work we have looked at the question of what happens if we view the edge set of a graph with loops as the union of edge sets of *trees* each of which comes from discarding a subset of the edges of the original graph. Using this structure we can directly define iterative algorithm in which we perform tree-based estimation using each of these embedded tree models in succession. To date we have performed experiments which indicate that, at least for certain types of graphical models, this approach leads to far more efficient algorithms for estimation and for accurate computation of error covariances.

h) We have recently developed a new approach to large-scale estimation that adapts and extends so-called Krylov subspace algorithms for solving large linear systems [26,35,36,68]. The key to the efficiency of such algorithms in applications such as solving discretized PDE's is being able to quickly calculate particular matrix-vector products. In the estimation context the matrix of concern is the data covariance matrix. Our contribution is roughly threefold. The first is demonstrating the applicability of Krylov subspace methods for large-scale spatial and space-time estimation for nontrivial classes of random field models--in fact models that are in some sense complementary to those for which multiresolution methods are directly applicable. The second contribution represents a nontrivial extension of Krylov subspace algorithms for the computation of quantities that are not typically of interest in other applications such as solving PDE's but are essential in our context, namely the calculation of estimation error covariances. Finally, the third contribution is the development of a first set of convergence results for our algorithm. While there are convergence analyses in the numerical linear algebra literature, the difference in our work is that we needed to consider the fact that the quantities of interest are described statistically (and, in particular, the data are corrupted by noise).

As described in [26,68] we have also developed an extension of the Krylov-subspace algorithm to deal with large-scale time-recursive estimation for space-time processes. In particular, the basic Krylov-subspace algorithm provides a fast algorithm for incorporating measurements assuming that certain covariance-vector products can be calculated quickly. In a recursive estimation context that algorithm can be used in the measurement update step assuming both that we can propagate the required error covariance *and* that the resulting covariance has structure that leads to fast matrix-vector products. Achieving these two properties involves the development of a second Krylov-subspace algorithm, in this case for the approximate propagation of the error statistics over time as the temporal dynamics are used to predict estimates to the next measurement update time. This is a nontrivial task, as it is not obvious that Krylov-subspace and conjugate gradient methods can be applied to the problem. However, in our work we have developed a concept for doing this which has shown its promise in preliminary testing.

i) We have developed a nonlinear/hybrid image analysis framework that combines our multiresolution estimation algorithms with the estimation of "hidden variables"

modeling data anomalies or abrupt changes (e.g., edges or discontinuities) in the scene being imaged [18,27,45]. The key to this extension is the use of the EM algorithm, coupled with our efficient multiscale estimation algorithm, in order to reconstruct or denoise images subject to these anomalies and abrupt changes. The methodology for this extension has now been developed, and we are nearing completion of the investigation of its application in a prototypical and important military imaging problem, namely the estimation of object shapes in laser radar range images. As with SAR and ISAR, such images are subject to significant outliers due to speckle, and we have demonstrated that we can use our new EM/Multiresolution framework not only to account for these anomalies but also to accurately separate a target from the background (by modeling the abrupt change in range or range slope when moving from background to target pixels as other hidden variables) and then to estimate target shape robustly.

2.3 Statistical Modeling and Estimation of Shape with Applications in Object Extraction and Recognition

The research described in this section represents one of the more recent and most exciting components of our research and one which we believe has substantial further promise for the future. In particular, the general objective of this part of our research is the development of statistically robust methods for segmentation and shape estimation with applications ranging from wide-area mapping to object recognition, and the results of our efforts in this area are developed in detail in publications [11,12,18,25,30-32,39,46,50,55-57].

j) In recent years a theory has developed for so-called curve evolution equations in which the objective is to smooth or evolve curves in images in order to find object boundaries or segment images. One rich framework for doing this involves the minimization of functionals related to the geometry of the curves. For example, minimizing curve length leads to a curve evolution in which the local speed of "shrinking" of a curve is determined by the curvature at each point. It had been known for some time that one way in which to apply this algorithm to segmentation involved the use of some image-guided metric for measuring the local length (and hence the curvature) of a curve. In particular, if one defines a local measure of curve length in terms of the local image gradient so that curves have much smaller length in regions of high image gradient, one can, in principle, design curve evolutions that will evolve to shortest length curves (in this adapted metric) that correspond to edges of regions or objects. Computing image gradients, of course, is a notoriously noisy process, so that ad hoc methods for obtaining smoothed image gradients were used. As a result, these algorithms had limited robustness and tended either to fail for very noisy images or to require excessive or ad hoc smoothing that limited the sharpness of the resulting segmentations. Moreover, the lack of a statistical formulation made it difficult to understand how these algorithms might be modified in order to enhance robustness. Furthermore, the evolutions had no natural way in which to grow rather than shrink, which required either a very carefully chosen initial condition for the curve or an ad hoc initial period of curve dilation before initiating curve shrinkage.

This state of affairs, as well as the intellectual objective of constructing a statistical framework for curve evolution, provided the motivation for our recent research. The simplest setting in which to understand the ideas behind our first work in this area is the binary segmentation problem in which we wish to partition an image into two subsets (neither of which needs to be connected--i.e., each can consist of an unknown number of connected components) so that the image pixel values have distinctly different mean values in each region. Equivalently, we need to find the curve C defining the boundary between these two subsets (so that this curve itself may consist of an unknown number of disconnected subcurves). The statistical optimality criterion we use to estimate C is simply

the negative of the square of the difference of the sample means computed in two regions separated by C (i.e., inside and outside). Gradient descent for the minimization of this functional then leads to a remarkably simple and robust curve evolution equation. In particular, rather than using local gradients to evolve the curves, this new evolution uses nonlocal and thus statistically more stable statistics, namely the sample means inside and outside, as drivers. The resulting evolution is quite robust to noise and in particular produces remarkably accurate segmentations of images even when starting from what are essentially arbitrary initial curves consisting of small subcurves distributed over the entire image domain. We have also shown how this method extends to the segmentation of an image into more than two statistically distinct regions which are not necessarily required to be disjoint (a potentially useful capability if occlusion is a significant issue).

k) In the second component of our work in this area we have adapted the flow described in **(j)** by including a global constraint that significantly aids performance for low-contrast images with complex region shapes. In particular, the evolutions defined by our work in **(j)** move a curve dynamically in order to increase the squared-difference between the sample means inside and outside of the curve. Since the objective is simply to increase the squared-difference, it is perfectly possible for the curve to evolve so that the means move in the same direction (e.g., both increase) but in a manner such that their difference also increases in magnitude. By modifying the evolution it is possible to ensure that the curve evolution always moves not only to increase the difference in means but also to drive each of the means in opposite directions. This modification does not affect computational complexity of the algorithm at all but produces rather remarkable segmentation for very complex images (e.g., for biomedical images of various types).

l) In [46] we describe research stemming from a curve-evolution interpretation and solution of a widely known combined image denoising and segmentation problem introduced by Mumford and Shah. This extension not only is of great intellectual significance in showing an explicit tie between curve evolution and statistical image analysis but also leads to some very interesting and important new image processing algorithms. In particular, our analysis has established that the solution to this problem involves a curve evolution coupled with the solution of elliptic PDE's inside and outside the curve. These PDE's characterize the optimal image estimate in each region based on the current estimated location of the curve. The behavior of these estimates near the current curve location then provide the driving term for the curve evolution, generalizing in a very elegant manner the work described in **(j)** in which the sample means inside and outside are used, together with image values on either side of the current curve location to drive the curve evolution. As can be seen in [46], the resulting algorithm has remarkable capabilities for segmenting images into multiple regions automatically without prior knowledge that there are multiple regions (or how many regions might be present). Moreover, because of its estimation-theoretic basis, the algorithm works equally well if there are missing data or data gaps as can occur for surveillance imagery (e.g., due to speckle, shadowing, or blockage due to cloud cover). In fact, using this same idea, we can extend this method to perform image magnification: we view our observed image as a subsampled version of a finer-scale image and then use our algorithm to smoothly interpolate to the higher resolution both inside and outside the curve without any blurring across the curve boundary. Our results demonstrate that this approach is far superior to any previously known method for image magnification.

2.4 Blending Physics and Statistical Learning for Image Reconstruction, Feature Extraction, and Fusion

In this section we describe our research on marrying sensor physics with statistics in order to develop robust methods for exploiting the information present in sensor data. The fundamental idea here is that a full, heavy use of fundamental physics (e.g., solving Maxwell's equations) is clearly inappropriate for sensor fusion since there are limitations in the "apertures" through which we view the phenomenon both from the input and output sides. In particular, the data that are typically available (e.g., to form a SAR image) are far too limited in extent and subject to too many sources of uncertainty and variability to warrant full solution of the inverse scattering problem in order to form an image. Fortunately, and complementary to the limitations in the observed data is the fact that the desired information we wish to extract from such sensor data--e.g., detections and classifications of objects--are far more limited than a complete inverse scattering solution. On the other hand, discarding all physics also is unwise, as the constraints implied by sensor physics can be used to reduce the apparent number of degrees of freedom in the data, thus enhancing the quality of any statistical analysis. The challenge is to determine the proper balance between physics/model-based methods and statistical/learning methods. This is a deep and enduring theme to which we believe we have made some contributions. Our work to date in this broad area is described in [4,8,10-11,23-24,37-38,40-41,48-49,51,53-54,58,65-66,69].

m) We have investigated a first principles estimation-theoretic approach to Synthetic Aperture Radar (SAR) imaging of moving scenes. In particular, we have extended the general SAR image formation problem, which aims to estimate radar cross section (RCS) in each pixel, to allow for the joint estimation of both RCS and a scene velocity vector in each pixel. However, the maximum likelihood estimation problem for the reconstruction of both of these quantities is a highly ill-posed variational problem unless we incorporate a regularizing prior model either on RCS variations or scene velocity (or both) across the image domain. The approach we have taken to addressing this problem is that of formulating variational problems corresponding to the joint MAP estimation of RCS and velocity fields over the scene domain. In particular, to capture the fact that we want to final image to be sharply focused, we have investigated the use of an L_1 penalty on the reconstructed RCS field. As Donoho has thoroughly discussed, the inclusion of such a penalty tends to favor sparse representations which in this case corresponds to the reconstruction of sharp images of bright scatterers. Interestingly, this term by itself leads to remarkably enhanced SAR reconstructions even when we know that there is no motion in the scene being imaged. In particular the presence of this sharpening term suppresses standard SAR sidelobes dramatically. Moreover, this regularizing term by itself allows us to estimate coarse scene motion--e.g., the mean velocity over a target region is accurately estimated simply with the inclusion of this L_1 penalty on the reconstructed RCS field and without any regularization of the velocity. However, as we begin to allow for varying velocities across the image scene (as is the case in typical SAR and ISAR imaging scenarios due to non-translational and nonrigid target motion), our preliminary results make it clear that we will need to introduce a regularizing prior for the velocity field as well.

n) A second component of our research in this area involves the development of a methodology that combines SAR scattering physics with observed SAR imagery taken at a number of different aspects to construct a SAR target model that captures the salient features that are robustly extractable from SAR data. Rather than taking the mathematical physics perspective of viewing this as a very ill-posed inverse scattering problem, we take advantage of the fact that salient features for SAR-based target discrimination are generally confined to a much lower-dimensioned set, corresponding to significant scatterers of different types. In our initial work in this area we have begun by limiting our attention to a small number of discrete scattering mechanisms, each of which has a well-defined, deterministic scattering response. The idea then is that individual SAR images are processed in order to extract estimated locations and types of features. Processing of these

individual images, however, results in the extraction of false features, missed detections of some actual features, and the misclassification of others due to noise, clutter, and to the limited aperture used in each individual SAR image. However, by associating features from multiple images using statistically optimal methods, we can obtain a consistent image that rejects spurious detections in individual SAR images and corrects for misses and misclassifications. Our results demonstrate the potential of this approach and also suggest ways in which to enhance it significantly and, more fundamentally, to understand more deeply how to exploit sensor physics in a statistically significant manner.

In particular, we have also taken a first set of steps aimed at relaxing the restriction on scattering types in order to capture some of the variability of scattering. Specifically, one of the important characteristics that is certainly captured in the full inverse scattering formulation but is lost if we insist on compressing each individual SAR view to a small, discrete set of types is the characteristic variability of the scattering response from a distinctive scatterer when we look at it from multiple viewing angles. If we could exploit that characteristic signature across views we would undoubtedly obtain better reconstructions of SAR scattering features and, in particular, a better indication of the robust and salient information that can be extracted from SAR images. In our initial work we have taken an initial and very limited look at how we might extend our framework to capture some of this variability for a specific scattering mechanism. In particular, some scatterer types (cylinders and so-called "top hats") appears as bright spots at different positions in images taken at different views due to the nonzero radius of the scatterer. This can lead to biases in the estimates of the location of the scatterer and to incorrect rejection of the feature if this characteristic is not recognized. However, if we include scatterer radius as another parameter to be estimated as part of the process of fusing information from multiple views, we can correct for this bias and correctly associate features extracted from different views that otherwise would appear to be originating from different locations.

o) Building on earlier work on multiresolution analysis of SAR imagery, we have taken a deeper look marrying SAR physics with nonparametric statistical learning methods for constructing probabilistic models for multiresolution imagery. In particular consider the formation of SAR imagery based on a given full aperture of data. If we use the entire aperture, we obtain imagery at the finest resolution resolvable using that data. However, to do this we in essence must assume that all scattering is isotropic, i.e., that the response from significant scatterers is constant across the entire aperture. For many important scattering mechanisms this is not the case at all, and this anisotropy is critical to distinguishing one scatterer type from another. Suppose then, that in addition to forming an image using the entire aperture, we also form three images each using half of the aperture: one image using the right half, one the left, and one using a centered half-aperture. If indeed there are anisotropic scatterers, we might expect that there would be differences in the responses in each of these half-apertures and hence in the images formed using them (note that these images would have pixel sizes twice as large as the ones in the finest scale imagery). Iterating this process, we can imagine forming a vector of images at each of a sequence of scales corresponding to progressively smaller subapertures. By looking across scale, then, we would expect not only to find statistical variability due to speckle but also any evidence of anisotropic scattering manifesting itself in statistically significant differences in pixel intensities in images formed using different subapertures.

Characterizing these differences in a statistically sound manner so that they can be exploited either for the extraction of features or for the recognition of objects, however, requires a significant departure from the linear-Gaussian modeling framework for multiresolution modeling on which we have focused most of our effort in the past. In particular, we now are faced with a multiresolution vector pyramid of images where the dimensionality of the vector is larger at coarser resolution (since forming a coarser resolution image requires a commensurably smaller subaperture of the SAR data, allowing more images to be formed). Furthermore and most importantly, much as in **(d)**, the

behavior across scale in this multiresolution pyramid is decidedly non-Gaussian (as, in particular, we are especially interested in significant outliers corresponding to characteristic behavior of particular anisotropic scatterers). In our work along these lines we have investigated the use of nonparametric density estimation techniques to build models capturing statistical variability from scale to scale.

p) Finally, in some very recent research we have explored the use of nonparametric statistics and statistical learning methods for problems of fusing information from completely different sensing phenomenologies. In doing this we have used several very different applications as vehicles. The first of these involves so-called functional MR imaging (fMRI). In this application, a patient performs a specific protocol, such as squeezing a ball, waving an arm, listening to words, speaking words, etc., while at the same time a sequence of MR images is taken of his or her brain. The challenge of fMRI, then, is to determine which voxels in a 3-D MR image volume involve activity in response to the protocol. Looking at a single candidate voxel, we have the problem of determining if there is any relationship between two time signals, one being the protocol (typically an on-off square wave signal, e.g., corresponding to squeezing a ball and then relaxing in a periodic manner) and the other being the time history of the MR image in the candidate voxel. While standard correlation methods (corresponding to assuming a linear relationship between these signals) are sometimes used, it is clear on looking at the signals that the relationship is highly nonlinear. As a result, we have the question of determining if, in some precisely measurable way, the information in these two signals is related. The approach we have taken is to use mutual information as a metric to quantify this relationship and have adopted the use of nonparametric statistical methods in order to estimate this quantity. At this point we have preliminary and very promising results on this application.

The second application involves the fusion of video imagery with acoustic signals sensed by microphones. In this case, the objective is to determine what action in the viewed scene is the source of the sensed acoustic signal (or what actions are responsible for the acoustic signal if there are several acoustic sources to be separated). We have developed a nonparametric statistics approach to finding the linear projection of the image scene that has maximal mutual information with the sensed acoustic signal. The results on preliminary imagery are striking in their ability to localize sources of sound.

III. Personnel

The following is a list of individuals who have worked on research supported in whole or in part by the Air Force Office of Scientific Research under Grant F49620-98-1-0349:

Prof. Alan S. Willsky, professor of electrical engineering, MIT
Dr. John Fisher, research scientist, MIT Lab. for Information and Decision Systems
Dr. Anthony Yezzi, postdoctoral researcher
Dr. Khalid Daoudi, postdoctoral researcher
Dr. Michael Daniel, recent Ph.D.
Dr. Seema Jaggi, recent Ph.D.
Dr. Ilya Pollak, recent Ph.D.
Dr. Austin Frakt, recent Ph.D.
Dr. Terrence Ho, recent Ph.D.
Dr. Cedric Logan, recent Ph.D.
Dr. Andy Tsai, recent Ph.D.
Mr. Michael Schneider, graduate student
Mr. Andrew Kim, graduate student
Mr. Dewey Tucker, graduate student
Mr. John Richards, graduate student
Mr. Martin Wainwright, graduate student
Mr. Erik Sudderth, graduate student
Mr. Junmo Kim, graduate student
Mr. Alex Ihler, graduate student

IV. Publications

The publications listed below represent papers, reports, and theses supported in whole or in part by the Air Force Office of Scientific Research under Grant F49620-98-1-0349:

[1] P.W. Fieguth, W.W. Irving, and A.S. Willsky, "Overlapped Tree Models for Multiresolution Modeling and Estimation," *IEEE Trans. on Image Processing,* Vol. 6, No. 11, Nov. 1997.

[2] P.W. Fieguth and A.S. Willsky, "Efficient Multiresolution Counterparts to Variational Methods in Surface Reconstruction," to appear in *Computer Graphics and Visual Information Processing*.

[3] W.W Irving and A.S. Willsky, " A Canonical Correlations Approach to Multiscale Stochastic Realization," accepted for publication in the *IEEE Trans. on Automatic Control.*

[4] S. Jaggi, W.C. Karl, H. Krim, and S. Mallat, A.S. Willsky, "High-Resolution Pursuit for Feature Extraction," *Applied and Computational Harmonic Analysis,* Vol. 5, 1998, pp. 428-449.

[5] M. Daniel, A.S. Willsky, D. McLaughlin, "A Multiscale Approach for Estimating Solute Travel Time Distributions,"*Advances in Water Resources,* Vol. 23, 2000, pp. 653-665.

[6] M.M. Daniel and A.S. Willsky, "Multiresolution Approximations to Fractional Brownian Motions," special issue of the *IEEE Trans. on Information Theory* on multiscale statistical analysis and its applications, Vol. 45, No. , April 1999, pp. 955-970.

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[8] S. Jaggi, A.S. Willsky, S. Mallat, W.C. Karl, "Object Recognition from Silhouettes Using High-Resolution Pursuit," accepted for publication in *Pattern Recognition.*

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[10] C.L. Logan, "An Estimation-Based Approach to SAR Imaging of Moving Objects," Ph.D. thesis, January 2000.

[11] I. Pollak, A.S. Willsky, H. Krim, "Image Segmentation and Edge Enhancement with Stabilized Inverse Diffusion Equations," *IEEE Trans. on Image Processing,* Vol. 9, Feb. 2000, pp. 256-266.

[12] I. Pollak, "Nonlinear Scale Space Analysis in Image Processing," Ph.D. thesis, Aug. 1999.

[13] R. E. Learned, A.S. Willsky, and D. Boroson, "Phase Estimation and Synchronization in Oversaturated Multiple Access Communications," in preparation for submission to the *IEEE Trans on Communications.*

[14] D. Tucker, H. Krim, S. Mallat, and D. Donoho, "On Denoising and Best Basis Selection," *IEEE Trans. on Information Theory.*

[15] T. Ho, P.W. Fieguth, and A.S. Willsky, "Efficient Space-Time Estimation Using Multiresolution Models," accepted for publication in *Automatica* .

[16] C.L. Logan, H. Krim, R. Chaney, and A.S. Willsky, "An Estimation-Theoretic Approach to SAR Imaging of Moving Scenes," in preparation for submission to the *IEEE Trans. on Image Processing.*

[17] A. Frakt, "Efficient Algorithms for Multiresolution Realization with Applications," Ph.D. thesis, Aug. 1999.

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[19] A. Frakt and A.S. Willsky, "Scale-Recursive Efficient Realization of Multiresolution Stochastic Models," 1998 IEEE Int'l. Conf. on Acoustics, Speech, and Signal Processing, May 1998.

[20] T. Ho, A. Frakt, and A.S. Willsky, "Multiresolution Stochastic Models and Algorithms for Space-Time Estimation," 1998 IEEE Information Theory Workshop, August 1998.

[21] T. Ho, P.W. Fieguth, and A.S. Willsky. "Computationally Efficient Multiscale Estimation of Large-Scale Dynamic Systems," 1998 IEEE Int'l. Conf. on Image Processing, Chicago.

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[23] J. Richards, "Modeling of SAR scattering responses from multiple images," Ph.D. thesis, in preparation.

[24] A.J. Kim, "Nonparametric Statistical Models for Multiple/Aperture SAR Image Pyramids," Ph.D. thesis, in preparation.

[25] A. Tsai, A. Yezzi, and A.S. Willsky, "A Fully Global Approach to Image Segmentation via Coupled Curve Evolution Equations," to appear in the special issue of *the Journal of Visual Communication and Image Representation* on partial differential equations in image processing;

[26] M. Schneider, "Computationally Efficient Random Field Estimation Algorithms Using Conjugate Gradient Algorithms," Ph.D. thesis, to be completed Jan. 2001.

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[30] I. Pollak, H. Krim, and A.S. Willsky, "Stabilized Inverse Diffusion Equations and Segmentation of Vector-Valued Images," 1998 IEEE Int'l. Conf. on Image Processing, Chicago. Oct. 1998.

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[34] A.B. Frakt and A.S. Willsky, "Computationally Efficient Stochastic Realization For Internal Multiscale Autoregressive Models," accepted for publication in *Multidimensional Systems and Signal Processing.*

[35] M.K. Schneider and A.S. Willsky, "A Krylov Subspace Method for Large Estimation Problems," ICASSP '99, Phoenix, March 1999.

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[37] A.J. Kim, J.W. Fisher, and A.S. Willsky, "Nonparametric Estimation of Aspect Dependence for ATR," presented at Algorithms for Synthetic Aperture Radar Imagery VI," SPIE Conference, Orlando, FL, April 1999.

[38] J.A. Richards, J.W. Fisher, and A.S. Willsky, "Target Model Generation from Multiple SAR Images," to be presented at Algorithms for Synthetic Aperture Radar Imagery VI," SPIE Conference, Orlando, FL, April 1999.

[39] A. Yezzi, A. Tsai, and A.S. Willsky, "Curve Evolutions for Image Segmentation Using Regional Statistics," invited paper at the IEEE Conf. on Image Processing, Kobe, Japan, Oct. 1999.

[40] C.L. Logan, A.S. Willsky, and H. Krim, "An Estimation-Theoretic Technique for Motion-Compensated Synthetic-Aperture Imaging," 1998 IEEE Int'l. Conf. on Image Processing, Chicago.

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[42] T.L. Ho, P.W. Fieguth, and A.S. Willsky, "Recursive Multiscale Estimation of Space-Time Random Fields," 1999 IEEE Int'l. Conf. on Image Processing, Kobe, Japan, Oct. 1999.

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[48] J. Richards, J. Fisher, and A.S. Willsky, "An Estimation-Theoretic Approach to 3-D SAR modeling from Multilook SAR Imagery," in preparation for submission to *Optical Engineering.*

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[52] R.E. Learned, A.S. Willsky, and D.M. Boroson, "Low Complexity Non-Coherent Near-Optimal Multiuser Detection for Oversaturated MA Communication," 37th Allerton Conference on Communication, Control, and Computing, Champagne-Urbana, IL, Oct. 1999.

[53] J.W. Fisher, III and A.S. Willsky, "Information-Theoretic Feature Extraction for ATR," 34th Asilomar Conference, Oct.29-Nov.1, 1999.

[54] J.A. Richards, J.W. Fisher, III, and A.S. Willsky, "An Expectation-Maximization Approach to Target Model Generation from Multiple SAR Images," Algorithms for Synthetic Aperture Radar Imagery VI," SPIE Conference, Orlando, FL, April 2000.

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[57] A. Tsai, A. Yezzi, and A.S. Willsky, "A Hierarchical Curve Evolution Approach to Smoothing and Segmentation Using the Mumford-Shah Functional," CVPR'2000.

[58] A.J. Kim, S. Dogan, J.W. Fisher, L. Potter, R. Moses, and A.S. Willsky, "Attributing Scatterer Anisotropy for Model-Based ATR," Algorithms for Synthetic Aperture Radar Imagery VI," SPIE Conference, Orlando, FL, April 2000.

[59] Tsai, A., Yezzi, A., and Willsky, A.S., "A Curve Evolution Approach to Medical Image Magnification via the Mumford-Shah Functional," to appear in MICCAI'00 (Medical Image Computing and Computer-Assisted Intervention).

[60] E. Sudderth, "Efficient Estimation Algorithms for Multiresolution Stochastic Models on Graphs," SM thesis in preparation.

[61] M.J. Wainwright and E. Simoncelli, "Scale Mixtures of Gaussians and the Statistics of Natural Images," Advances in Neural Information Processing, Vol. 12, 2000.

[62] M.J. Wainwright, E. Simoncelli, and A.S. Willsky, "Random Cascades of Gaussian Scale Mixtures for Natural Images," to be presented at ICIP'00.

[63] M.J. Wainwright, E. Simoncelli, and A.S. Willsky, "Multiresolution Wavelet Cascade Stochastic Models with Applications to Natural Imagery," accepted for publication in the special issue of *Applied and Computational Harmonic Analysis* on wavelet applications.

[64] J.W. Fisher, A.T. Ihler, and P. Viola, "Learning Informative Statistics: A Nonparametric Approach," Adv. in Neural Information Processing Systems, Nov.29-Dec.4, 1999.

[65] A. Ihler, "Nonparametric Learning of Dynamic Models," SM thesis, Aug. 2000.

[66] J. Kim, "The Use of Mutual Information and Statistical Models in Functional MR Imaging," SM thesis, Aug. 2000.

[67] J.W. Fisher, A. Tsai, C. Wible, J. Kim, A.S. Willsky, and W.M. Wells, "Analysis of Functional MRI Data Using Mutual Information," submitted to *IEEE Trans. on Information Theory.*

[68] M.K. Schneider and A.S. Willsky, "Krylov Subspace Algorithms for Space-Time Oceanography Data Assimilation," IGARSS-2000, Hawaii, July 2000.

[69] Kim, J., Fisher, J..W., Wible, C., Wells, W.M., and Willsky, A.S., "Spatio-Temporal Analysis of fMRI Data Using Information Theory and Markov Random Fields," to appear in MICCAI'00 (Medical Image Computing and Computer-Assisted Intervention).

V. INTERACTIONS/TRANSITIONS

In this section we summarize the various interactions and transitions associated with research supported by AFOSR Grant F49620-98-1-0349, focusing on the last year of this grant (we refer the reader to previous progress reports for information on previous activities in these areas).

Participation/Presentation at Meetings

In addition to presentations at professional conferences, we have been involved in the following other meetings during the past year:

(1) Prof. Willsky has continued to have regular meetings with engineers and researchers at Alphatech to discuss collaborative research in the area of SAR-based ATR and, more recently, in multiresolution modeling and fusion for global awareness in connection with an Alphatech project under AFOSR's New World Vistas initiative. In addition, our work on graphical models has direct relevance to DARPA's Dynamic Database Program, and we have initiated discussions with Alphatech on topics of mutual interest.

(2) In January 2000 Prof. Willsky delivered the keynote address at the AFRL-AFOSR Workshop on Future Directions in Sensor Fusion and Automatic Target Recognition, held at Eglin AFB.

(3) At the request of AF LGen (Ret.) Lincoln Faurer, President of the National Correlation Working Group (and former Director of the National Security Agency), Prof. Willsky participated as one of the lead panelists on data and sensor fusion at the May 2000 NCWG Workshop on Information for the Warfighter, held at Fort Monroe, Virginia, in collaboration with the Aerospace C2ISR Center in Langley.

Consultative and Advisory Functions

During the year, Prof. Willsky has been engaged in the following activities relevant to the research being performed under our AFOSR grant:

(1) Prof. Willsky has regularly acted as a consultant to Alphatech, Inc. in a number of research projects including ones that represent direct transitions of the technology being developed under our AFOSR Grant.

(2) Over the past 2.5 years Prof. Willsky has acted as co-chair (with Dr. Wendy Martinez of ONR) of a tri-service working group on the role of probability and statistics in command and control. Prof. Willsky was the principal author of the report produced by this panel.

(3) In October 1998, Prof. Willsky was appointed to the Air Force Scientific Advisory Board. During his first year in this position, Prof. Willsky participated in the S&T Review of AFRL/SN and the relevant parts of AFOSR supporting SN, and he also was an active participant on the Intelligence and Vigilance Panel for the 1999 AF/SAB Summer Study on Technology Options to Leverage Aerospace Power for Operations Other than Conventional War. During the Fall of 200, Prof. Willsky served on the S&T Review Panel for AFRL/IF and the associated AFOSR programs, and he has recently completed his effort as a member of the Technology Panel in this year's AF/SAB Summer Study on

AFC2: The Way Ahead (a topic specifically requested by the Air Force Chief of Staff), including being the principal author of recommendations on sensor and data fusion.

(4) At the request of Mr. E. Zelnio of AFRL/SN, Prof. Willsky participated as a member of an ad-hoc panel helping Mr. Zelnio and AFRL with its plan for technology insertion to meet both short- and intermediate-term objectives related to the "Tanks under Trees" initiative requested by the Air Force Chief of Staff in response to needs identified in Kosovo operations.

Transitions

The following are the transitions of our research that are taking place:

(1) Our multiresolution SAR discrimination algorithms, most recently for the classification of nonisotropic scattering behavior, are being transitioned to Alphatech for inclusion in advanced model-based ATR algorithms. The points of contact on this are Dr. Robert Washburn, Dr. John Wissinger, and Dr. Gil Ettinger.

(2) Our work on multiresolution SAR analysis and high-resolution pursuit have been transitioned to Alphatech under a Small Business Technology Transfer contract from the Army Research Office to transition our multiresolution mapping and estimation methods to military applications. The points of contact at Alphatech for this are Dr. Robert Washburn and Mr. Thomas Allen.

(3) Our efficient methodology for multiresolution mapping and data fusion are being transitioned to Alphatech as part of an SBIR program, through NIMA, on fusion of multiresolution and multipass data to produce high-fidelity terrain maps. The point of contact is Mr. Thomas Allen.

(4) Our current work on building SAR scattering models from multiple-view SAR imagery is being carried out in close contact with Alphatech engineers to ensure rapid transition. The points of contact are Dr. John Wissinger and Dr. Gil Ettinger.

(5) Our work on stabilized inverse diffusion equations for nonlinear image segmentation has been transitioned to Alphatech for the segmentation of IR imagery as part of an AFRL Sensors Directorate program on SAR-FLIR fusion. The point of contact on this is Mr. Thomas Allen.

(6) We have recently initiated discussions with Alphatech on the transition of our work on statistical image segmentation and region estimation using curve evolutions, both to DARPA's Dynamic Database (DDB) Program and to imaging projects in medical imaging and video surveillance. The points of contact on this are Dr. Joel Douglas, Dr. John Wissinger, and Dr. Gil Ettinger.

(7) We have also begun transitioning our most recent work on covariance extension and graphical models to an Alphatech SBIR on road network estimation, an adjunct to DARPA's DDB Program. The point of contact is Dr. Joel Douglas.